**Out-of-plane Autonomous Orbit Control**

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***Abstract:*** *The autonomous orbit control (AOC) enables the maintenance of a satellite on a reference orbit with little ground intervention, which is presented in the first part of the article. Orbit control is done by filtering the position/velocity resulting from a navigator and by adjusting models of the evolution of various parameters. The controlled parameters are the orbit ascending node crossing date (in-plane control), and the right ascension of the ascending node (out-of-plane control). Another part of this article deals with the method of selection of slots for maneuver realization, to ensure the best control of the various orbital parameters, as the whole orbit may not be available for maneuver. Lastly, an interesting aspect is presented, that consists in controlling the trajectory even if the satellite is not (yet) in its nominal orbit (introduction of a "transition orbit").*

***Keywords:*** *Autonomous Orbit Control, out-of-plane control, on board maneuvers.*

## 1 Introduction

The Autonomous Orbit Control (AOC) enables keeping a satellite close to a reference orbit with little ground intervention. AOC has been experimented on DEMETER, a Myriade satellite (CNES line of micro-satellites) [1] [2]. For this mission, the aim of the experiment was to control the satellite orbit in its plane and to compute and perform the needed station keeping maneuvers on board and in an autonomous way (and thus counteracting the decrease of the semi major axis).

It is also interesting to perform out-of-plane control. This control proves to be necessary for Sun-synchronous phased orbits for example. This article presents the changes made on DEMETER AOC to simultaneously control in-plane and out-of-plane parameters. Controls are done by filtering the measurements resulting from a navigator and by adjusting models of the evolution of various parameters. The controlled parameters are the orbit ascending node crossing date (in-plane control), and the right ascension of the ascending node (out-of-plane control). The reference models are quite simple, corresponding to a linear evolution as a function of time. The gap between those reference models and their corresponding values are also filtered. A control window is defined for each gap and when the resulting filtered evolution goes outside this window, maneuvers are computed and executed.

Controlling the trajectory with respect to a reference orbit can be made difficult with the impossibility to execute maneuvers at any point of the orbit. Some parts of the orbit are dedicated to the realization of parts of the mission which cannot be done simultaneously with the execution of a maneuver. Thus this article deals with the method of selection of slots for the maneuver realization, to ensure the best control of the various orbital parameters. More particularly, the algorithm searches, in priority, for slots placed near the nodes of the orbit in order to carry out the out-of-plane control. For the in-plane control, more frequent, the positions of pure tangential maneuvers are computed so as to control the evolution of the orbit eccentricity.

Lastly, an interesting aspect is to be able to move the satellite on its orbit while continuing to carry out the mission or to be able to restart this mission even if the satellite is not yet at its nominal position (for example after a survival event, creating an orbital drift). This aspect is managed by the introduction of an orbit known as "transition orbit"; the AOC will perform maneuvers in order to follow this particular orbit.

## 2. Autonomous Orbit Control generalities

The orbit control is done by keeping parameters inside a suitable window. The in-plane controlled parameter is the ascending node crossing longitude [3] or the ascending node crossing time (and the mean eccentricity vector). For the out-of-plane control, the most adapted parameter is the orbit right ascension of the ascending node (Ω). In the following paragraphs, we deal only with the out-of-plane control as the in-plane one has been approached in several papers [1] [2] [3] [4].

### 2.1 Determination of the controlled parameters

The method used to control these parameters has already been presented. It consists in filtering measurements (position/velocity information given by a "navigator", using measurements from a GPS or Galileo receiver). The method used for the in-plane control, is also applicable to the out-of-plane one. The filtering is designed to determine the evolution model of orbital parameters and also of gap between reference model and their corresponding orbital parameter. These models are simply first or second degree polynomial [4]. For the out-of-plane control, we introduce a fitting of the right ascension of the ascending node with respect to a reference model.

The model chosen for the right ascension of the ascending node is a first degree polynomial. The difference between this model and a reference is computed and filtered. Under the only disturbance of Earth and Moon/Sun potentials, the evolution of this gap is parabolic (see Fig. 1). The model adjusted for this discrepancy is a second degree polynomial (Eq. 1).

$$\delta\Omega = A\cdot(t-t_0)^2 + B\cdot(t-t_0) + C \tag{1}$$

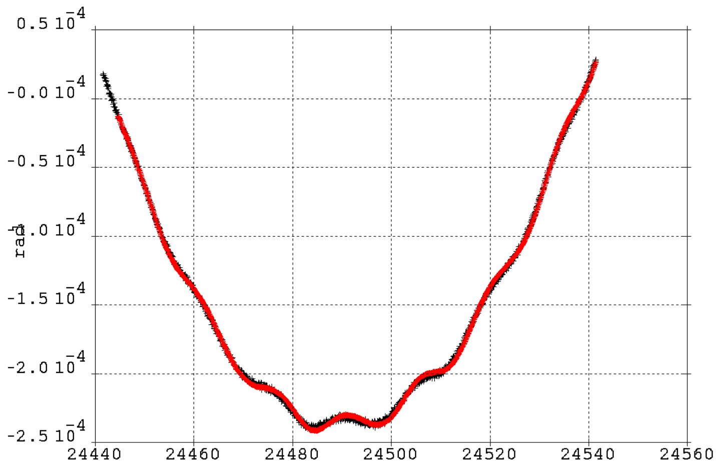


**Figure 1. Evolution of the right ascension of the ascending node gap**

Residual oscillations observed around the parabola are due to the Moon/Sun potential. It is possible to filter these oscillations by increasing the filter time constant (constant time greater than or equal to fourteen days, half-period of disturbances due to the potential, see Fig. 2). Filtering this disturbance has the advantage of reducing maneuvers number, because they are not generated to follow the oscillations; but the disadvantage is that the convergence duration of the filter is increased.

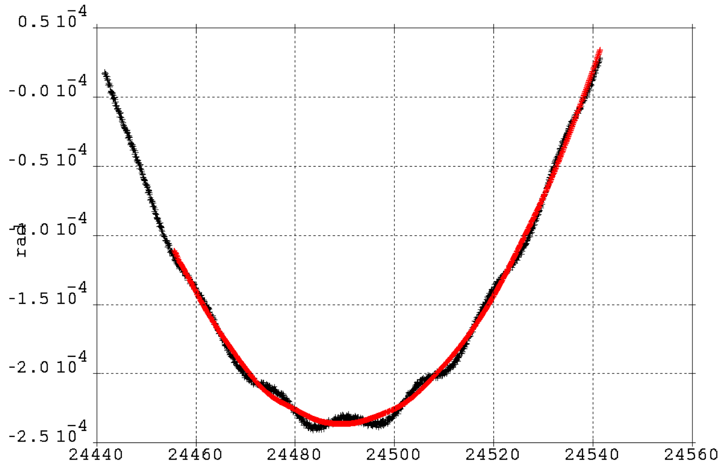


**Figure 2. Filtering of Moon/Solar disturbance**

### 2.2. Reference parameters

To control the out-of-plane offset, it must be given to the AOC a theoretical law for the right ascension of the ascending node. As a first approximation, the right ascension of the ascending node follows a linear evolution. Knowledge for this parameter on board, can be improved by introducing harmonic corrections due to tesserals terms of the Earth potential, whose effects tend to shift right ascension as a function of the longitude. Right ascension of the ascending node can be written:

$$\Omega_{ref}(t) = \Omega_{ref}(t_0) + \dot{\Omega}_{ref} \cdot (t - t_0) + \delta\Omega_{corr} \tag{2}$$

With:

$$\delta\Omega_{corr} = a_0 + \sum_{k \geq 1} \mathrm{a}_k \cos(kL) + b_k \sin(kL) \tag{3}$$

L represents the longitude of the ascending node. The number of harmonic coefficients uploaded depends on precision with respect to the reference orbit, as it is described later.

### 2.3. Maneuvers determination

A maneuver must be scheduled when the controlled parameter gets out of the control window allocated (see Fig. 3).

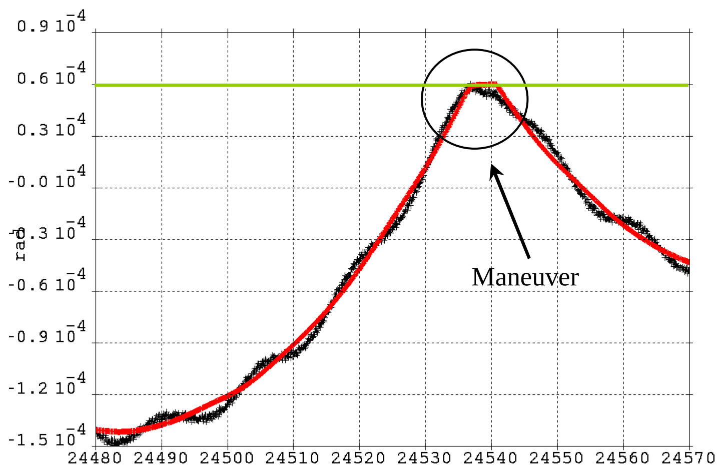


**Figure 3. Out-of-plane maneuver**

This maneuver will be computed in order to change the slope of the offset evolution, as it is presented in the following figures (slopes are represented in color, Fig. 4).

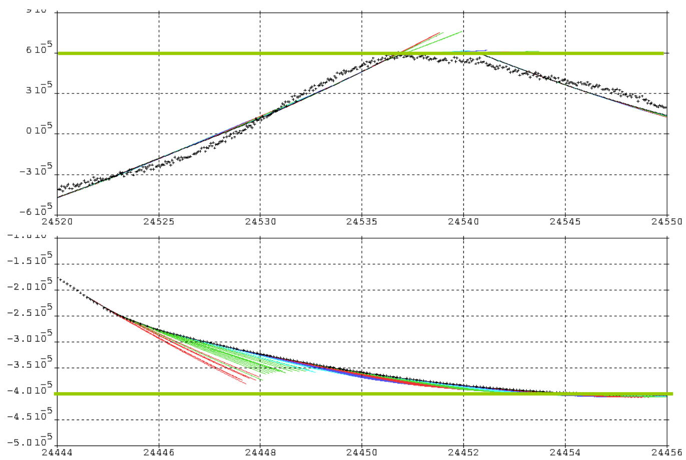

**Figure 4. slope modification**

The modification of the slope is calculated to bring back the gap value in the window. It consists in targeting the top or the bottom of the window, depending on how the gap is getting out of it. Examples of types of maneuvers are given below (Fig. 5). The green color represents the evolution of the gap before the maneuver, the red one, once the maneuver is performed.

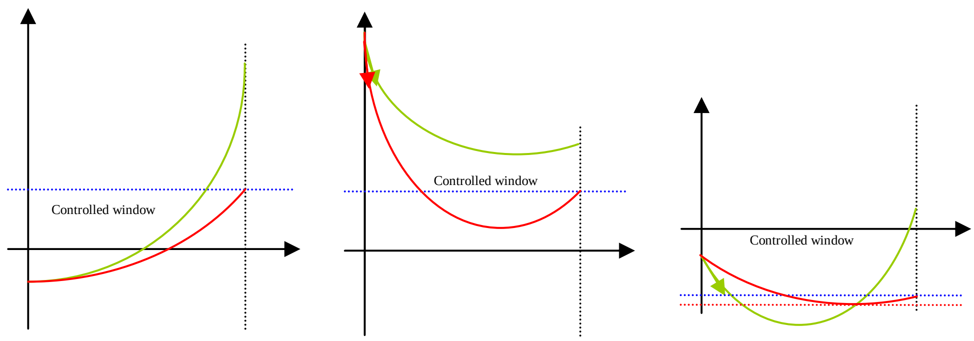


**Figure 5. Type of maneuver**

Once the slope variation is fixed ($\Delta B$), the increment is transformed into an out-of-plane $\Delta V$ using the Gaussian equation (Eq. 4).

$$\Delta V_w = V \cdot \frac{\Delta i}{cos(\alpha)} \text{ and } \Delta i = \frac{\Delta B}{\frac{3}{2}\left(\frac{R_T}{a}\right)^2 \frac{n\,J_2}{\left(1-e^2\right)^2} sin\,i} \tag{4}$$

where:

$V$ is the satellite velocity,
$\Delta B$ is the slope increment,
$R_T$ is the Earth radius,
$J_2$ is the second zonal term of the Earth potential,

$e = \sqrt{e_x^2 + e_y^2}$ , is the orbit eccentricity,
$a$ is the semi major axis,
$i$ is the inclination,
$n = \sqrt{\frac{\mu}{a^3}}$ , the mean motion.

## 2.4. Implementation of maneuvers in the filters

Maneuvers, once made, are taken into account in the filters, in order to avoid a reset and thus an interruption of service during the filters convergence. Once more, the Gaussian equations give the variation of the orbital parameters and the offset as function of velocity increments, in and out of the plane (Eq. 5).

$$
\begin{aligned}
&\Delta a = \frac{2a}{V}\Delta V_t && \Delta\Omega = \frac{\sin(\alpha)}{V\sin i}\Delta V_w \\
&\Delta e_x = \frac{2\cos(\alpha)}{V}\Delta V_t && \Delta\dot{\Omega} = \frac{3}{2}\left(\frac{R_T}{a}\right)^2 \frac{n J_2}{\left(1-e^2\right)^2}\sin i\cdot\Delta i \\
&\Delta e_y = \frac{2\sin(\alpha)}{V}\Delta V_t && \Delta\alpha_m = -\frac{\sin(\alpha)}{V\tan i}\Delta V_w \\
&\Delta i = \frac{\cos(\alpha)}{V}\Delta V_w && \frac{\Delta\dot{\alpha}_m}{\dot{\alpha}} = -\frac{3}{V}\Delta V_t
\end{aligned}
\tag{5}
$$

Out-of-plane offset is represented by a second degree polynomial (Eq. 1). Taking maneuvers into account simply consists in adding the $\Delta V$ effect to this model, which is directly the slope $B$, as it is written in the equation 6.

$$B_{after\,man} = B_{beforeman} + \Delta\dot{\Omega} \tag{6}$$

## 3. Simulations – Results

The orbit control performance depends on orbit disturbances not taken into account in the reference orbit. These disturbances are essentially atmospheric drag, (if the orbit is low) and the Moon/Sun potential (if the orbit is high). The importance of these forces is modulated by solar activity. The bigger the solar activity is, the stronger atmospheric drag is; thus for a "high" orbit, with a very low solar activity, the drag will be low and the influence of the Moon/Sun potential will be relatively more important. Under such conditions, the semi major axis may increase and it should be necessary to perform braking maneuvers to counteract this effect.

Simulations for different altitudes (500 km, 650 km, 800 km) and different solar activity (strong and weak) are presented in Table 1. below.

| Altitude | 500 km | | 650 km | | 800 km | |
|---|---|---|---|---|---|---|
| Mean solar activity (w/m²/Hz) | 80 | 200 | 80 | 200 | 80 | 200 |
| Maximum in-plane gap (km) | 0.67 | 1.99 | 0.59 | 0.43 | 0.33 | 0.41 |
| Maximum out-of-plane gap (km) | 0.60 | 0.58 | 0.96 | 0.86 | 0.70 | 0.70 |
| Total $\Delta V$ (m/s) | 11.9 | 57.6 | 17.6 | 20.9 | 6.4 | 7.4 |
| In-plane $\Delta V$ (m/s) | 5.7 | 53.4 | 0.7 | 5.3 | 0.3 | 1.3 |
| Out-of-plane $\Delta V$ (m/s) | 6.2 | 4.2 | 16.9 | 15.6 | 6.1 | 6.1 |
| Number of maneuvers | 1930 | 3389 | 1316 | 1684 | 1700 | 1423 |
| Out-of-plane maneuvers | 431 | 322 | 288 | 295 | 693 | 710 |
| Number of maneuvers with $\Delta a < 0$ | 77 | 7 | 503 | 9 | 529 | 26 |

**Table 1. Results**

Those simulations were conducted without taking account of slots for the achievement of maneuvers. It can be observed that out-of-plane control is not sensitive to solar activity as the number of maneuvers has the same order of magnitude for both low and high solar activity.

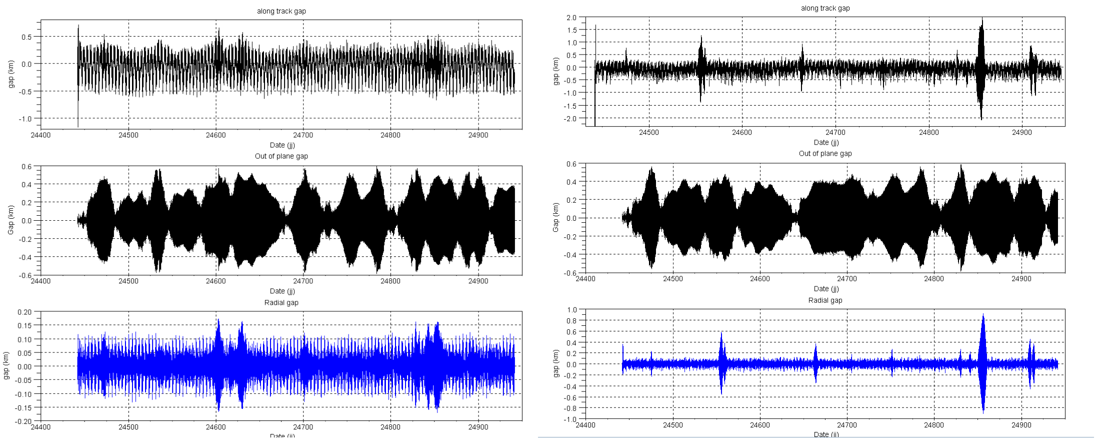


**Figure 6. Altitude 500 km – low / strong solar activity**

If we focus on the in-plane results for high solar activity, we can see peaks that are produced by the out-of-plane control (see Fig. 7 above), because the method implemented gives priority to the out-of-plane control to the detriment of eccentricity (see fig 7 below).

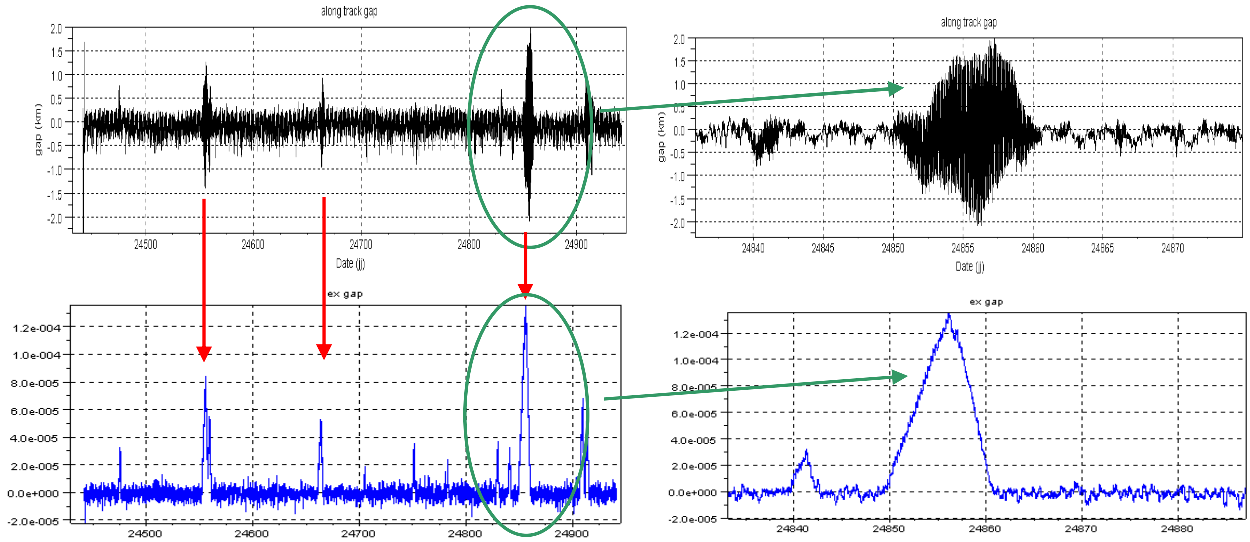


**Figure 7. Focus on the in-plane error (above) and eccentricity (below)**

The out-of-plane maneuvers are one boost maneuvers, and when there is no constraint on their location, the first opportunity is chosen: the ascending node. Under this condition, if a lot of out-of-plane maneuvers are done, the eccentricity will drift. And yet successive out-of-plane maneuvers are necessary as each one tries to reduce the slope of the out-of-plane gap as long as this gap has not reached the window border (see Fig. 4). This behavior is illustrated by figure 8, showing the maneuvers type and the out-of-plane controlled parameter.

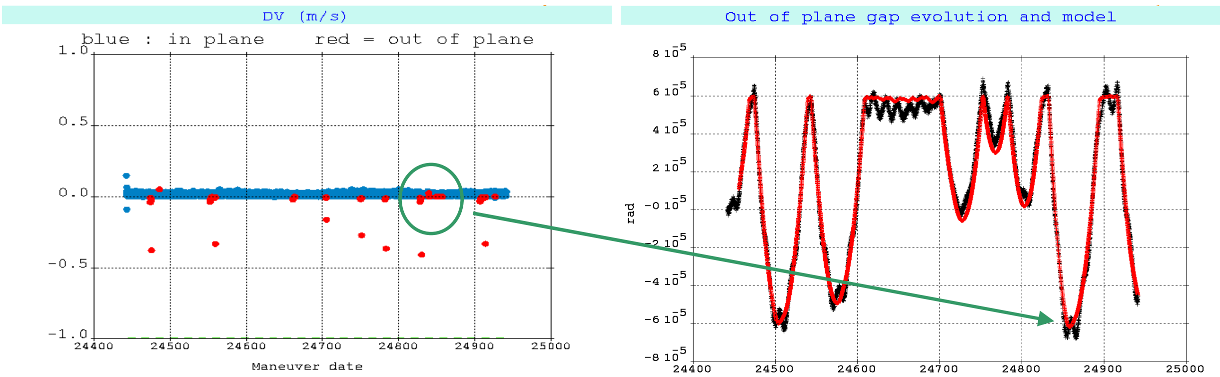


**Figure 8. Out-of-plane maneuvers and parameter evolution**

## 4. Reference orbit

Knowledge of a reference orbit is necessary both on-board and on ground:

- On-board: it is the heart of the algorithm, it gives the reference model of the controlled orbital parameters. Then the satellite can compute maneuvers when the satellite orbit moves away from the reference.
- On ground: without the reference orbit, the orbit determination is more complicated, as the time and range of the maneuvers are not known. With it, the position of the satellite is known over a large time horizon without orbit determination and, what is more important, the reference orbit enables fine pointing of ground stations without intervention or communication with the control centre.

It is important to "put" in the reference orbit model, the disturbances that we do not wish to see corrected by AOC. The orbit control enables to compensate the secular drifts on the semi major axis and the inclination, in order to control the orbit position and the right ascension of the ascending node. Long periodic effects of the disturbances are neutral to the overall propellant consumption, but short and medium-sized periods effects are annoying, because "exciting" the control and inducing overconsumption; the short and medium-sized periods effects are therefore integrated into reference orbit.

$$
\begin{aligned}
a(t) &= a_0 + \sum_{n,k}^{n\,max,k\,max} \left( a_{n,k} \cdot cos(n \cdot \alpha_M + k \cdot L_{NA}) + b_{n,k} \cdot sin(n \cdot \alpha_M + k \cdot L_{NA}) \right) \\
e_x(t) &= e_{x_0} + \sum_{n,k}^{n\,max,k\,max} \left( a_{n,k} \cdot cos(n \cdot \alpha_M + k \cdot L_{NA}) + b_{n,k} \cdot sin(n \cdot \alpha_M + k \cdot L_{NA}) \right) \\
e_y(t) &= e_{y_0} + \sum_{n,k}^{n\,max,k\,max} \left( a_{n,k} \cdot cos(n \cdot \alpha_M + k \cdot L_{NA}) + b_{n,k} \cdot sin(n \cdot \alpha_M + k \cdot L_{NA}) \right) \\
i(t) &= i_0 + \sum_{n,k}^{n\,max,k\,max} \left( a_{n,k} \cdot cos(n \cdot \alpha_M + k \cdot L_{NA}) + b_{n,k} \cdot sin(n \cdot \alpha_M + k \cdot L_{NA}) \right) \\
\Omega(t) &= \Omega_0 + \dot{\Omega}_0 \cdot (t - t_0) + \sum_{n,k}^{n\,max,k\,max} \left( a_{n,k} \cdot cos(n \cdot \alpha_M + k \cdot L_{NA}) + b_{n,k} \cdot sin(n \cdot \alpha_M + k \cdot L_{NA}) \right) \\
\alpha(t) &= \alpha_0 + \dot{\alpha}_0 \cdot (t - t_0) + \sum_{n,k}^{n\,max,k\,max} \left( a_{n,k} \cdot cos(n \cdot \alpha_M + k \cdot L_{NA}) + b_{n,k} \cdot sin(n \cdot \alpha_M + k \cdot L_{NA}) \right)
\end{aligned}
\tag{7}
$$

The form of the reference orbit is defined in equation 7. This form is composed of a secular part and a set of harmonics, $a_{n,k}$ and $b_{n,k}$, (different for each orbital parameter) that represent the influence of the Earth potential (short and medium-sized period effects). The harmonic part of the decomposition is function of orbit position and satellite longitude. The precision of the model depends on the number of harmonics used onboard (parameters *nmax* and *kmax*).

The influence of the number of uploaded harmonic parameters is represented on the two curves below (for altitude equal to 500 km on the left, below and 800 km on the right above). They represent the along-track difference between an orbit rebuilt with all the harmonic parameters and an orbit rebuilt with the number of harmonic parameters selected for on board decomposition.

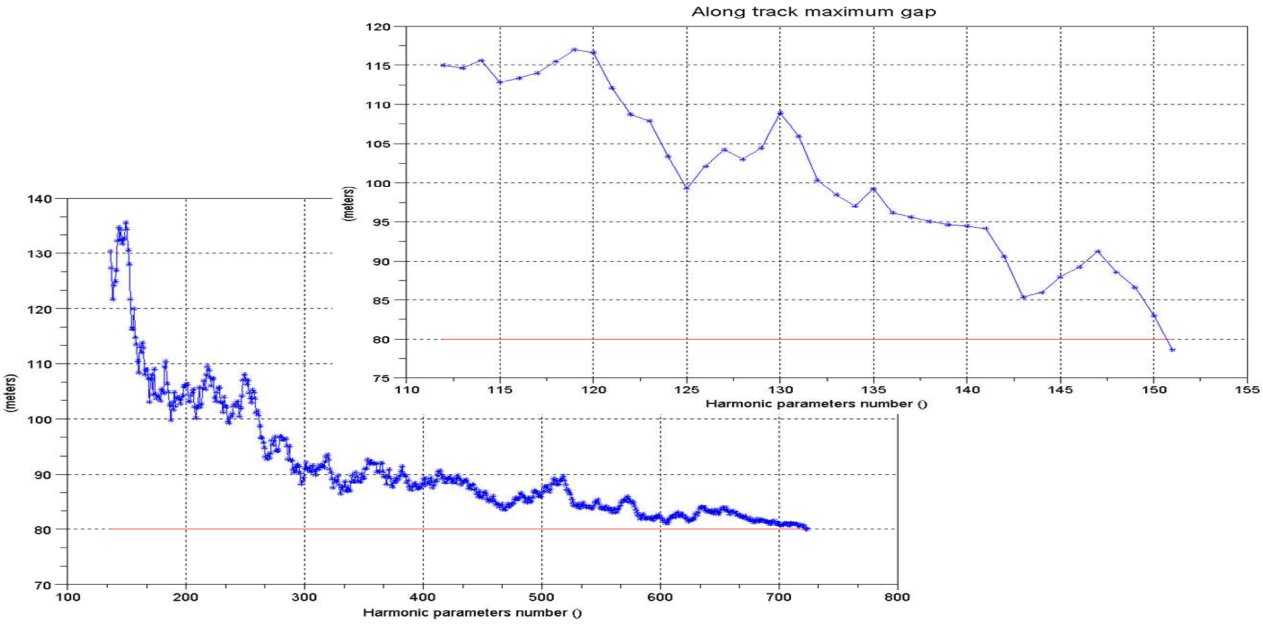


**Figure 9. Influence of the number of harmonic parameters used**

## 5. Maneuver slots

All the orbital positions are not always available for the achievement of orbit control maneuvers. Most of time a number of constraints prohibit portions of orbits for maneuvers. Those constraints may originate in risk of instruments dazzling, conflicts with station visibilities (the satellite cannot maneuver while it downloads telemetry) or constraints linked to the achievement of the mission. For example, in the case of DEMETER satellite, the slots were positioned very close to ground station visibility periods so that along track $\Delta V$ effects could be bounded. These different constraints lead to the definition of areas where maneuvers are allowed, areas called "maneuver slots" (see Fig. 10).

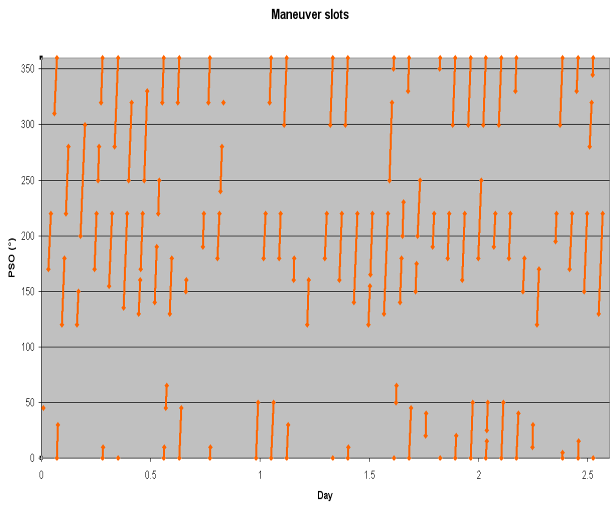


**Figure 10. Maneuver slots**

The impossibility to achieve the maneuver at any point on the orbit may cause a degradation of the performance. We can observe a degradation of eccentricity (see fig 11) and also sometimes an impossibility to carry out the out-of-plane control, if slots are not available at the nodes of the orbit.

It becomes necessary to choose the best slots based on the type of maneuver to do. For example, in case of in-plane control, it is not possible to simply take the first slot available to perform a maneuver because the eccentricity would drift from the frozen one (see Fig. 11).

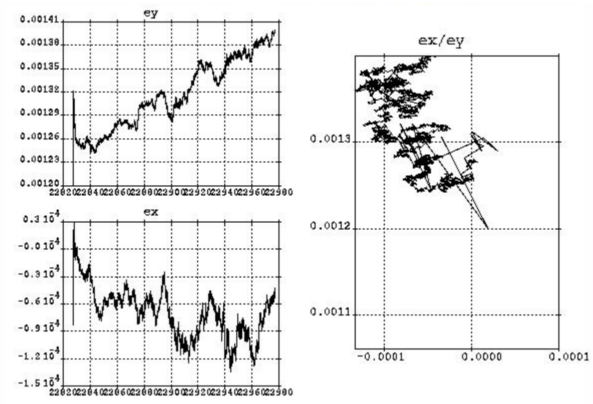


**Figure 11. Control of eccentricity without choosing the maneuver slot**

Maneuvers in inclination take precedence over the tangential maneuvers as they enable to combine the out-of-plane correction with semi major axis. The correction in inclination is not critical (less frequent), so it can be delayed in case orbit nodes are not included in a maneuver slot. In this case, as the need to control the plan may be urgent (for example with high drag), we cannot afford to cancel the maneuver and the correction is redirected to an in-plane control strictly. A slot selection algorithm is presented in figure 12.

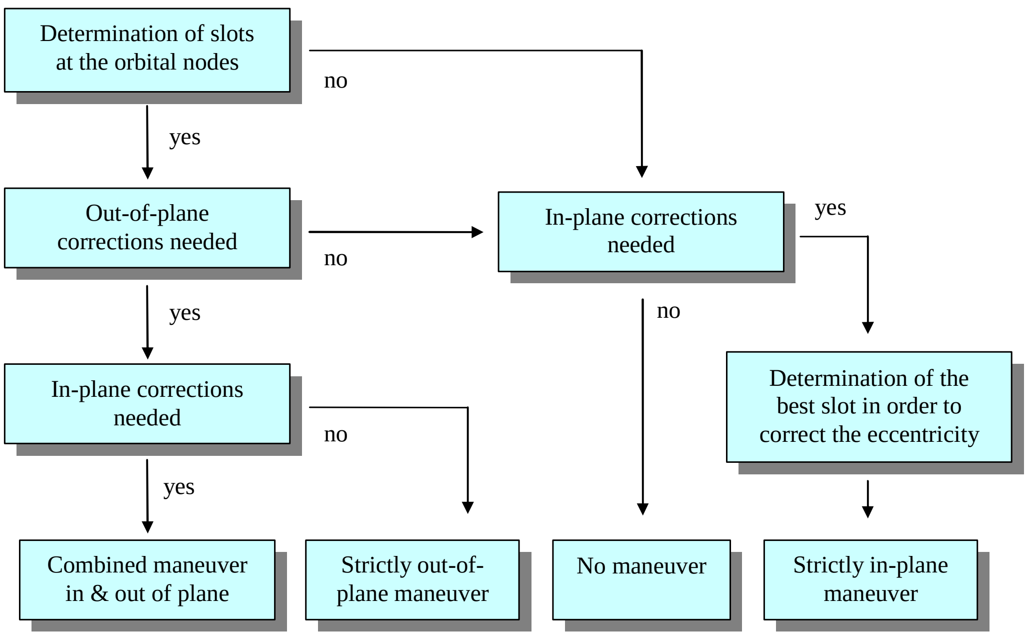


**Figure 12. Slot selection algorithm**

With a good slot distribution over the orbit, the AOC performances stay at the same level, for standard solar activity. Figure 13 shows two simulations realized, first without taking into account slots, and second with the slots. The performances accuracy is not really changed.

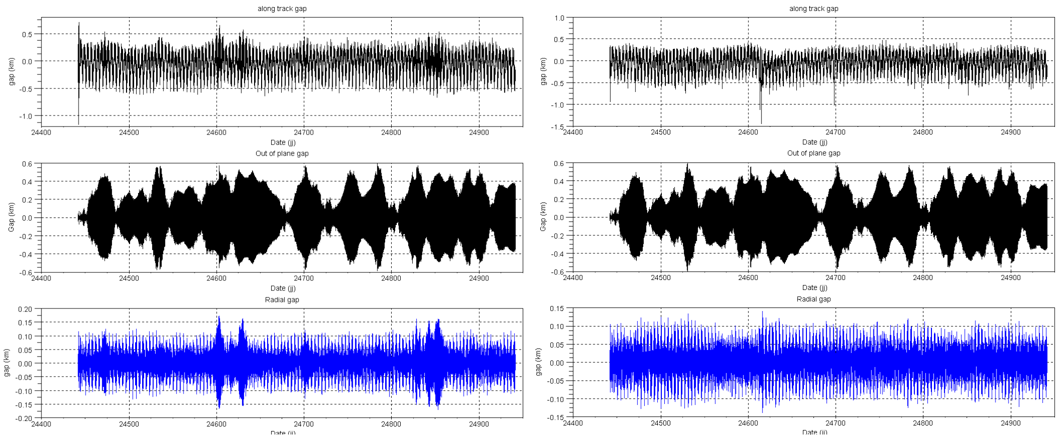


**Figure 13. Accuracy comparison without/with slots**

In case of high solar activity, for which atmospheric drag leads to quick orbital parameters changes, the weakness of the method is amplified. Peaks appearing because of the eccentricity drift are accentuated (see Fig. 14). As shown before, those peaks are due to the successive achievement of out-of-plane one boost maneuvers. The degradation appears only for the in-plane control.

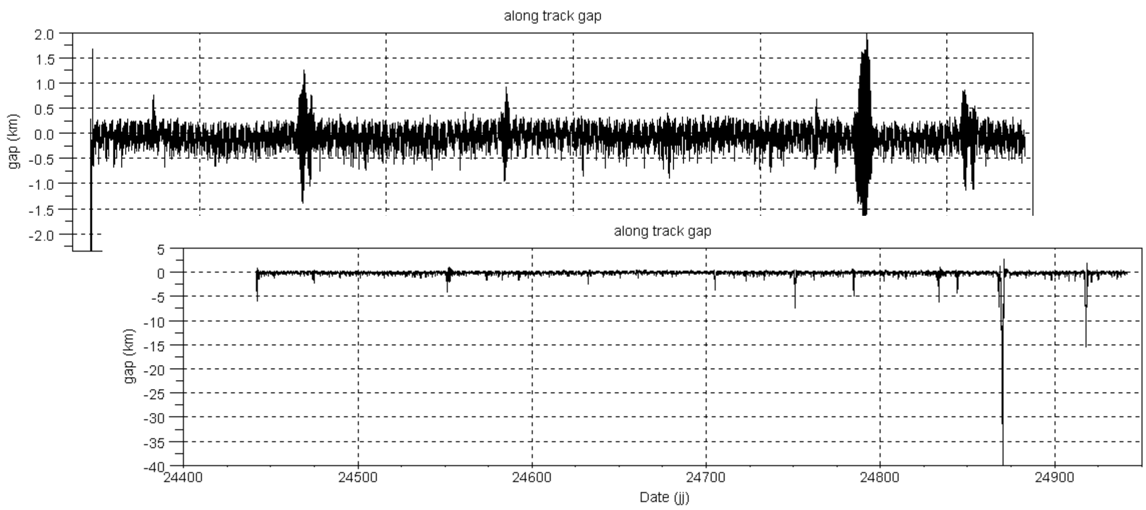


**Figure 14. Along track accuracy**

## 6. Drifting reference orbit

The need for a drifting reference orbit appears when satellite has drifted from its reference orbit and that we want to use the AOC to make it return near it. This orbit can also be used if the mission wants to perform a modification of the satellite nominal position with the AOC, in order to use the advantages of this mode of operation. In such a case the control center continues to work with a reference orbit and does not need to compute and upload maneuvers.

A drifting orbit is a transient orbit which allows to move from an orbit to another using the AOC. The two reference orbits may not be too far away because the drifting orbit is still constrained. The concept presented here, consists of just a modification of the secular parameters of the reference orbit. This orbit can be used for example after a satellite survival event, during which the satellite may have slightly drifted. It can also be used to return near the reference orbit after a collision avoidance maneuver.

The next example presents a very simple "drifting reference orbit": an orbit with a drift on the semi major axis (noted "*V*"). For the implementation of such drifting orbit, the controlled and the reference parameters must be modified accordingly. As the controlled in-plane parameter is the ascending node crossing time, its evolution is represented in the algorithm by the equation (8):

$$t_{AN} = t_{AN_0} + T_{orb} \cdot N + d \cdot N^2 \tag{8}$$

With $t_{AN}$, the Ascending Node crossing time, $T_{orb}$, the orbital period and *N*, the number of orbit since the first ascending node crossing. In first approximation, the relation between *V* and the parameter "*d*" is given by Equation 9:

$$d = \frac{3}{4} \cdot \frac{V}{a} \cdot T_{orb}^2 \tag{9}$$

The model of the transition orbit (Eq. 7) must be modified by adding a term to the on-orbit position parameter formula as shown in Equation 10.

$$\alpha(t) = \alpha_0 + \dot{\alpha}_0 \cdot (t - t_0) + \ddot{\alpha}_0 \cdot (t - t_0)^2 + \sum_{n,k}^{n\,max,k\,max} (\ldots) \tag{10}$$

The order two coefficient of the polynomial is given by equation (11):

$$\ddot{\alpha}_0 = -\frac{3\pi}{2 \cdot T_{orb}} \cdot \frac{V}{a} \tag{11}$$

With those modifications the in-plane difference between the two orbits (the orbit delivered by AOC and the drifting reference one) is represented in Figure 15. It remains a parabolic evolution due to the approximate determination of $\ddot{\alpha}_0$. To improve the result, it would be necessary to determine a better relation between the parameter given in the AOC algorithm (parameter "*d*", Eq. 9) and the parabolic evolution of the on-orbit position. But, as this transition orbit should be used during a short period, the value given by Eq. 11 should be enough.

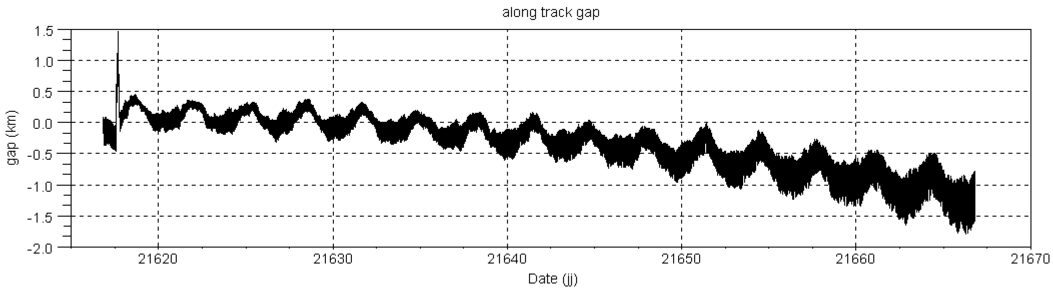


**Figure 15. Along track accuracy**

## 7. Conclusion

In this article we have presented the changes made to the AOC algorithm successfully implemented on DEMETER (out-of-plane control). This control uses the filtering generic concept developed for the in-plane control and validated by implementation on DEMETER satellite. We also have also introduced the notion of “drifting orbit” as a way to extend the use of AOC to cases where the satellite is far from its nominal position.

Several things must be modified or updated in order to improve the autonomous orbit control method. First of all, it may be interesting to determine out-of-plane maneuvers consisting in two boosts, each boost realized at a different orbit node (ascending then descending). Then the eccentricity vector may not drift anymore, as it could be possible to control it with dissymmetrical boosts.

The out-of-plane control method could also be modified in order to reduce the number of successive boosts each time the controlled parameter reaches the control window limit. It should possible to perform a maneuver in order to reverse the evolution of the controlled parameter instead of several boosts trying to decrease the slope (before finally reverse it).

And finally, a new method has to be developed for the out-of-plane control of a drifting orbit that could be used at the end of the satellite mission lifetime, when inclination is no longer controlled.

## 8. References

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